MicroElectroMechanics in Electrical Metrology

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Abstract. Microelectromechanical systems (MEMS) will have an important role in metrology. If a piece of a single crystal silicon forms a spring, metal surfaces define a geometry, and forces are produced by an electric field in a vacuum, the system is presumably stable. Owing to a capacitive readout and an electrostatic control, the system wastes no power. In addition, compared to semiconducting devices micromechanical components are large in size. A low 1/f noise is expected. We show that a MEMS can be used to realize both a dc and ac voltage reference, ac/dc converter, dc current reference, low frequency voltage divider, microwave and millimeter wave detector,etc. Unfortunately, existing MEMS technologies where silicon forms electrodes cannot be used owing to extra charges in silicon dioxide or on its surface; metallization of the surface is needed. Finally, we report preliminary results of our dc voltage reference showing a long term stability lower than 10^{-6}.

I. Introduction

Microelectromechanical systems (MEMS) are nowadays widely used in sensors; accelerometers, gyroscopes, microphones, pressure sensors, etc. They are made of silicon and applied, e.g. in cars. Bulk micromachining is used in applications where mass is needed while surface micromachining suits well to form light membranes for detection of pressure. Recently, SOI wafers (Silicon On Surface) are entering micromachining. Wafers are specially tailored for sensors. Apparently, MEMSs will be applied not only is sensors but also in actuators, oscillators, energy converters, etc.

Some efforts has already been done to exploit micromachining in metrology [??,??,??]. In this paper we describe their general features to show that they are excellent candidates for precise devices for metrological instruments. However, a lot has to be done before they replace existing references. MEMSs can be widely utilized in metrology but we focus here only on electrical metrology. Finally, we discuss the progress of our voltage reference and bring out some fundamental problems related to their use.

II. General Features

A. Dynamics

Lets consider two parallel plates; another is moving in a piston mode. The gap x between them responses to force as

$$m\frac{d^2x}{dt^2}+\eta\frac{dx}{dt}+kx=\frac{\epsilon A}{2\left(\ell-x\right)^2}\left(U+U_n\right)^2+F_m+F_n \quad , \tag{1}$$

where m is the mass of the moving plate, k is the spring constant, and η describes friction usually related to gas damping. F_m is the force term related to pressure p as $F=pA$, acceleration a as $F=ma$ or to any other mechanical force. Following to the dissipation-fluctuation theorem $\langle F_n\left(t\right)F_n\left(t+\tau\right)\rangle=2k_BT\eta\delta\left(\tau\right)$, where k_B is the Boltzmann constant, T is the absolute temperature and $\delta\left(t\right)$ is the Dirac delta function. The power spectral density function of the displacement fluctuation can be given as $S_{n,f}=4k_BT\eta=4k_BT\omega_m/(kQ_m)$, where $Q_m$is the quality factor of a mechanical system resonating at $\omega=\omega_m=\sqrt{k/m}$. U is the ac or dc voltage applied between electrodes and U_n denotes the noise voltage arising from electrical dissipation or from amplifiers, if only from electrical dissipations then $S_{n,U}=4k_BT\left|Z_{tot}\right|^2/\operatorname{Re}Z_e$, where Z_{tot} is the total impedance between the voltage terminals and Z_e only the contribution from an electrical circuitry.

There are three features in Eq. 1 which are of great relevance in metrology. First, the force is proportional to the voltage squared and thus a MEMS is acting as a true rms converter. Second, the force is inversely proportional to the gap squared and thus even a relatively small voltage across a tiny gap induces forces higher than other mechanical forces. Third, after evacuating gas from a gap, the Q-value can arise over 10.000. Mechanical noise becomes low related to voltage induced forces; precise measurements become possible.

B. Noise

An uncertainty in a capacitance measurement is fundamentally limited by thermal noise. If a noise is arising from electrical dissipations or from a preamplifier, then $S^{e}_{\Delta x/\ell}=k_B\left(T+T_a\right)/\left(\omega_{rf}Q_eE_e\right)$, where ω_{rf} is the readout frequency, Q_e is the quality factor of an LC circuit and $E_e=CU_{rf}^2/2$ gives the electrostatic energy. Apparently, the capacitance is tuned with a coil and the amplifier is noise matched to the LC circuit. From Eq. 1 we find $S^m_{\Delta x/\ell} = 2k_BT/(\omega_m Q_m E_m)$, where $E_m = k\ell^2/2$. is the maximum spring energy. The rf voltage U_{rf} is limited by the pull in voltage and thus $E_e \lessapprox 0.1E_m$. In practise $T > T_a$, and thus mechanical noise dominates, if $\omega_{rf}Q_e \gtrsim 5\omega_m Q_m$. This condition can be used as a guideline for electronics. In addition, it is good to be aware of low frequency electrical dissipations parallel with a component; electrical noise may become converted into mechanical fluctuations. On the other hand a stray capacitance deteriorates displacement detection. In general, with an appropriate readout electronics, the displacement of a moving plate can be detected so accurately that its random motion can be monitored. Therefore, most cases mechanical dissipations set limits to the resolution of a micromechanical device.

Noise in micromechanical devices results from electrical or mechanical dissipations and can easily be estimated; a resolution of the device is very predictable. For high motion, noise mixing effects may become important as it does when a MEMS is operated close to critical points. If so a complete Langevin equation such as that given in Eq. 1 have to be solved with numerical methods.

C. The pull-in voltage

>From Eq. 1, we get $dx/dU = \sqrt{2x\epsilon A/k}/(\ell - 3x)$. In the range $x > \ell/3$ the derivative is negative and no stationary solution exists. Instead, the gap slumps and a moving plate will stick a fixed one. The critical point $x = \ell/3$ is reached, when

$$U = U_{Pi} = \sqrt{\frac{8k\ell^3}{27\epsilon A}} \quad . \tag{2}$$

Note that Eq. 2 only approximates the pull-in voltage. In general, the pull-in voltage depends on how a stationary displacement is related to force and also the geometry of a component. A stable spring and structure lead to the time independent characteristic voltage.

D. Electromechanical Coupling

If a voltage across a MEMS is gradually increased, a part of the energy will be stored into a capacitance and a rest moves a cantilever leading to an increase in mechanical energy. Mechanical energy takes it all when the system is close to the pull-in voltage. Even though a component is biased far away from the critical point markedly amount of energy will be stored in a mechanical form. The electromechanical coupling in a micromechanical system is much higher than it is e.g., in piezoelectric transducers. Actually, it is strong electromechanical coupling and low dissipations which make microelecromechanics so alluring for sensors.

E. Electrical Feedback and Noise Reduction

Owing to a narrow gap markedly forces are resulted from low driving voltages. This enables us to exploit electrical feedback to compensate for a displacement resulted either from mechanical or electrical forces. Direct and linear force-to-voltage or voltage-to-voltage conversions become possible. A high sensitive device may have a resonance at low frequency thus a strong negative feedback may lead to an unstable device. To ensure high feedback gain more sophisticated controllers should be adopted.[[1]]

A feedback can be used to linearize the system but also for active damping. Gas damping ,e.g., in accelerometers is required to have a flat frequency response. Damping increases noise. If the speed of a cantilever in vacuum is detected and the voltage trying to decelerate a movement is fed back to the electrodes, the system behaves as filled with gas. The difference is, however, that the noise temperature of this artificial gas equals to the noise temperature of the readout system; it can be as low as 1 K or even lower.

F. Resonance Tuning

Due to the strong coupling between electrical and mechanical energies, mechanical parameters such as a spring constant can be altered with voltages. We already showed that damping can be served by an electronics. Electrodes carrying the same voltage in both sides of a grounded cantilever decrease the resonant frequency still keeping the cantilever in the middle. E.g. in ac/dc converters a low resonant frequency is attractive to enable to measure amplitudes of low frequency signals. A spring constant cannot only be looses but also tighten.

G. Charge Drive

A voltage drive limits the displacement to the range from 0 to $\ell/3$. If a charge rather than a voltage is controlled, the force is no more dependent on position and a gap can be made infinitely small. A charge drive is difficult owing to a leakage and its detection. Driving an ac current $I = \widehat{I}_{ac} \sin \omega_{ac} t$, where $\omega_{ac} > \omega_m$, through a component, the average force becomes $F = (I_{rms}/\omega_{ac})^2 / (2\epsilon A) = q_{eq}^2/(2\epsilon A)$, where "oscillating" charge I_{rms}/ω_{ac} corresponds to stationary charge q_{eq}. With a ac current drive an induced ac voltage becomes

$$U_{rms} = \frac{1}{\epsilon A}\left(\ell - \frac{1}{\epsilon Ak}\frac{I_{rms}}{\omega_{ac}}\right)\frac{I_{rms}}{\omega_{ac}} \quad . \tag{3}$$

The ac voltage reaches the maximum when $I_{rms} = \omega_{ac}\sqrt{\epsilon Ak\ell/6}$ and in that point the voltage equals to the pull-in voltage as shown in.Fig. 1. It is immune to changes in current and thus a simple moving plate can be used as a stable voltage reference.[[4]]

III. Standards

A. Precise ac and dc voltage source

A stable ac voltage source is extremely simple. Driving an ac current via a moving plate into a fixed electrode and stabilizing an current into the voltage maxima in the level of 10^{-4} a stable and frequency independent ac voltage source is completed. In practise, a parasitic capacitance may prevent from making an ideal current source modifying an $I_{rms}U_{rms}$ characteristics as shown in Fig. 1. The problem can be avoided by adding a coil in parallel with the system, but the method, unfortunately, engages the frequency. The better solution is to use a piston mode and to make an actual capacitance as high as possible Also guarding of a stray capacitance with an extra electrode solves the problem. To eliminate vibrations and gravity a seesaw type component prefers to a cantilever.

We have realized a stable dc voltage source by using a seesaw type component with four electrodes. It is made of using bulk micromachining. Figure 2. shows the block diagram of the electronics. The electrodes in the left hand side are used to detect a displacement and a dc voltage into the upper electrode of the left hand side imposes the displacement into the set value. The ratio of the capacitors is compared to the voltage divider acting as a set value for the controller. When the ratio is one third of the full gap, the dc voltage equals to the pull-in voltage.

According to Eq. 1 the effective spring constant becomes zero when $x = \ell/3$ and the voltage to displacement transfer function can be written as

$$h(j\omega) = \frac{\Delta x(\omega)/\ell}{\Delta U(\omega)/U_{Pi}} = \frac{9C}{\eta}\frac{1}{j\omega(1+j\omega)}$$

where $\tau_m = m/\eta$. The system acts as an integrator and a low pass filter in series. Consequently, a controller could have a pole at $\omega = 1/\tau_m$, but not an integrator at all. To eliminate a systematic error we adopted a $\mathrm{PI}^{3/2}$-controller [[1]] The controller comprises P and D-terms, and a circuit having a frequency dependent gain $G \approx 1/\sqrt{j\omega}$. The circuit is realized by combining several RC-circuits. The method locks the seesaw in the critical point without being disturbed by variations in controller parameters.

The system is not symmetric around the critical point and thus noise or external fluctuations may cause a shift in dc voltage. A brief analytic calculation shows, however, that the voltage shift is small and if origins from thermal noise, constant in nature. Our preliminary experiments with a new voltage reference are given in section III.

B. AC/DC Converter

The most obvious application of a MEMS in metrology is to measure the balance between forces arising from ac and dc voltages. A seesaw as that illustrated in Fig. 2 can be use to realise an ac/dc converter. The dc voltage controlled by a capacitance bridge compensates for the force produced by an ac voltage source. In balance, the ac voltage equals to the dc voltage. To lower the resonant frequency a large and heavy seesaw should be used or the resonant frequency should be reduced electrically as discussed above.

We have carried out some preliminary ac/dc experiments but owing to extra charges on silicon dioxide surfaces and asymmetric CV characteristics, the devices were not yet good enough for accurate measurements.

C. Current Reference

If a constant current is charging a capacitance, the voltage is steadily increasing. A moving plate set in parallel with the charged capacitor C_q, will slump when the pull-in voltage is approached. Due to the contact between the electrodes the capacitor is discharged and the moving plate returns to its original position. The current is related to the frequency as $I_{dc} = fC_{tot}U_{Pi}$, where $C_{tot} = C_q + C$ combines the external capacitance and that of the moving plate. Since the capacitor can be traced to resistance, frequency f to a stable crystal oscillator, and the pull-in voltage is time independent, the method can be used as a stable current reference. To speed up the measurement the length of the periods synchronised to the current rather than the frequency should be measured. The method is extremely simple but electrodes should go through a great number of contacts perhaps making the system impractical.

D. Low Frequency Voltage Divider

High voltages can be measured using a capacitive, resistive or inductive voltage divider. Such dividers either load a source, warm up, or their output impedance becomes very high at low frequencies. To use a MEMS as a voltage divider is illustrated in Fig. 3a. The control voltage in the lower electrode compensates for a high voltage in the upper side of the moving plate. If the area of the upper electrode equals to that of the lower one, then $U_{high} = U_{low}(\ell_{high}/\ell_{low})^2$.

We have performed a preliminary experiment using a dc voltage source up to 600 V and a micromechanical scale [[5]] as a detector. The device functioned as expected but to obtain repeatable results and to avoid an electrical breakdown the set-up should be placed in vacuum and the support for the upper electrode should be made with care; this was not done in our preliminary experiment.

E. High Frequency Standards

The force between two electrodes is determined by the RMS value of an ac voltage for all frequencies If we have a 50 Ω microstripline characterized by a linewidth of w_{50} and a height of h_{50} and in a force sensing section the line is characterized by w_{rf} and h_{rf}, then $F = U_{ind}^2(w_{50}/h_{50})\epsilon d_{rf}/(2h_{rf})$.Here d_{rf} is the length of the force sensing portion and U_{ind} is the incident voltage. Since the force is independent of the line width w_{rf} it should be made as wide as possible to minimize the influence of a stray capacitance. Since the ratio w_{50}/h_{50} is more or less fixed, the force can be maximized by increasing the length d_{rf} and minimizing the height h_{rf} Presumably, the length will be limited by dissipations and the thickness by millimeter wave reflections, thus a compromise is necessary.

The sensitivity of a millimeter wave detector can markedly be improved by modulating an incident wave to activate a mechanical resonance; a displacement is amplified by a factor of Q_m A detailed calculation shows that a resonating millimeter wave detector based on a MEMS is superior to a bolometer recently applied to detect millimeter waves. The MEMS detects the electric field and thus it is not disturbed by phonon fluctuations as it is when the power is converted to heat and a temperature rise is detected.

IV. Experiments

We have performed experiments concerning a stable ac voltage source, high voltage divider and dc voltage reference. In this paper only recent experiments obtained from our dc reference will be discussed in detail.

In most MEMS components at least one electrode is made of silicon, usually contaminated with silicon dioxide. Owing to defects and impurities silicon dioxide and its surface can carry extra charges.[[3]] A change in electric field changes a population in trapped states and the force between electrodes accordingly. A distance from silicon to silicon dioxide surface is about 1.5 nm leading to a low tunneling rate at least to surface states and thus the force between electrodes shifts slowly. The effective pull-in voltage drifts in time. The drift is not a very serious problem because it settles in process of time. The problem is force fluctuations owing to random tunneling of electrons into surface or trap states and back to silicon. Owing to a high tunneling resistance and capacitance, traps induced force fluctuations appear only at low frequencies. This can be partly eliminated by reversing the voltage.

Figure 4 shows the power spectral density function of the reference voltage and the insert figure the Allan variance accordingly. In our experiment the voltage reversing did not markedly improve the long term stability as expected. Before the data analysis the drift and a sinusoidal daily variation in temperature causing about 10 ppm variation in voltage were eliminated. If the point of operation differs from the turning point, the voltage fluctuation becomes much higher as shown in Ref. [[6]].

Our preliminary results are very promising, the long term stability is less than 10^{-6}. We expect that it is limited by charge fluctuations in silicon dioxide. We are convinst on that because the power spectral density function of the voltage fluctuation can be approximated from the drift data assuming only that the silicon dioxide layer is about 1.5 nm in thickness. Our results indicate also that there are traps in silicon dioxide and also on its surface. Very likely electrical asymmetry in a silicon silicon dioxide structure prevents us from eliminating low frequency fluctuations by reversing the voltage. After replacing silicon electrodes with a non-oxidising metal, much better results are expected. Since the MEMS makes it easy to get near any voltage as a reference, vwery likely they will gradually replace zener diodes in precise instruments.

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